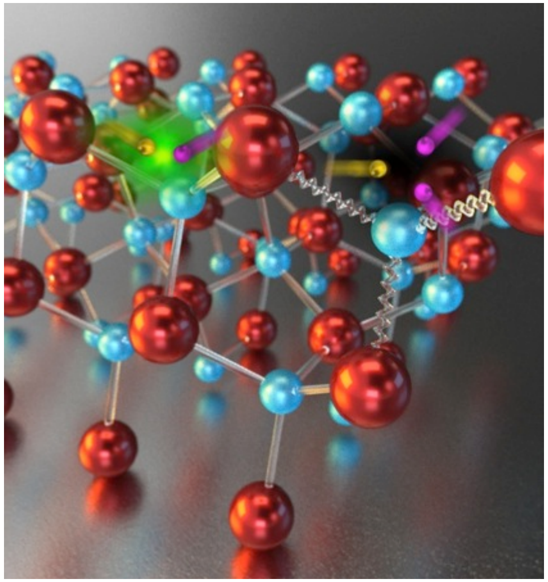
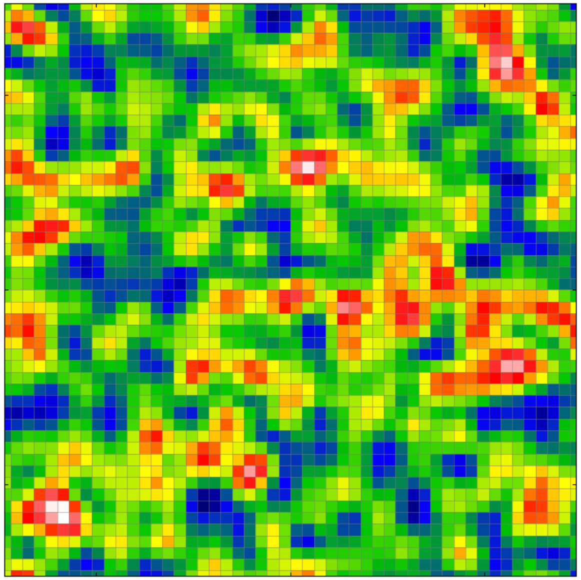
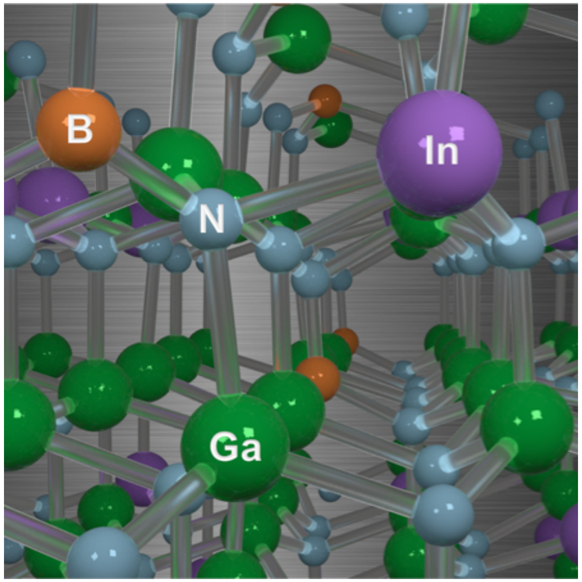


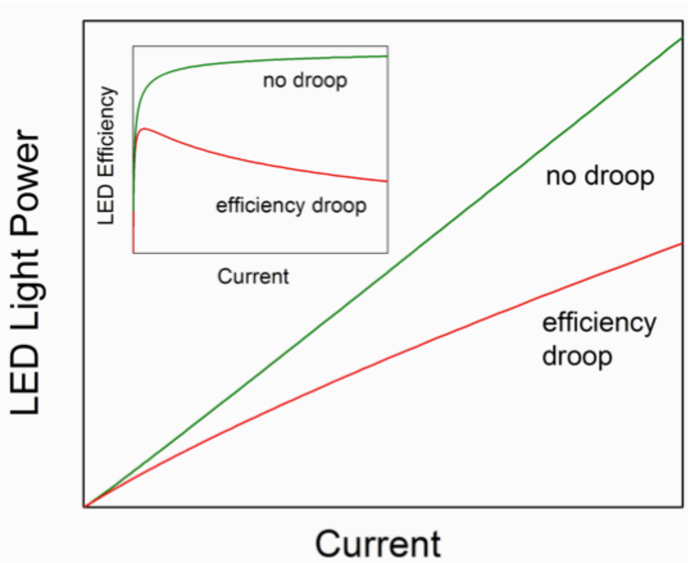




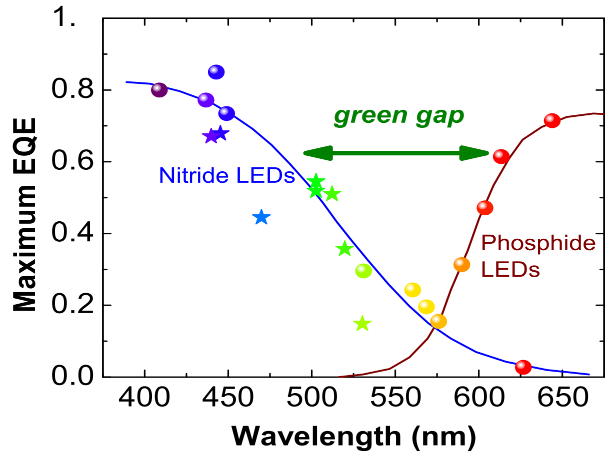
Understanding and mitigating droop in nitride LEDs

Emmanouil (Manos) Kioupakis
Materials Science and Engineering, University of Michigan

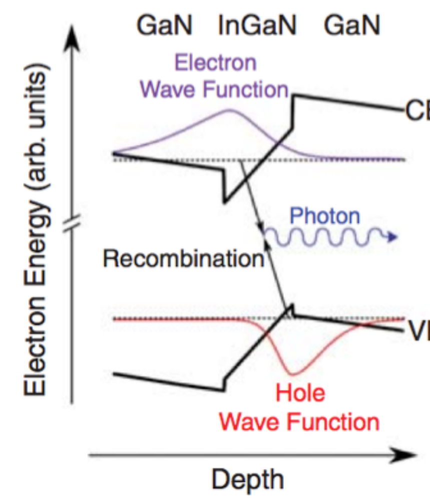
Challenges with nitride LEDs



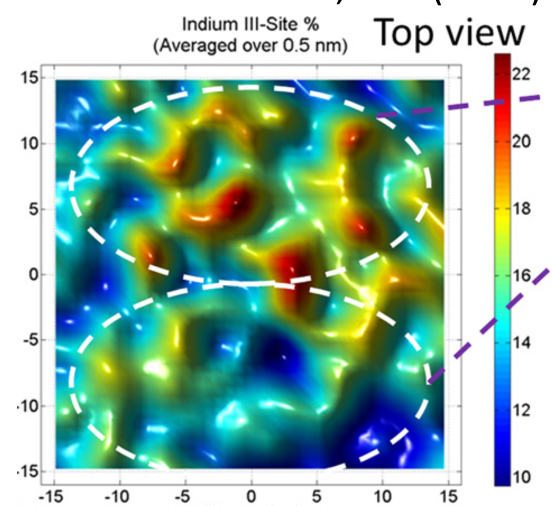
Piprek, *phys. status solidi (a)* **207**, 2217 (2010).



Auf Der Maur *et al.*, *Phys. Rev. Lett.* **116**, 027401 (2016).



Speck and Chichibu, *MRS Bull.* **34**, 304 (2009)

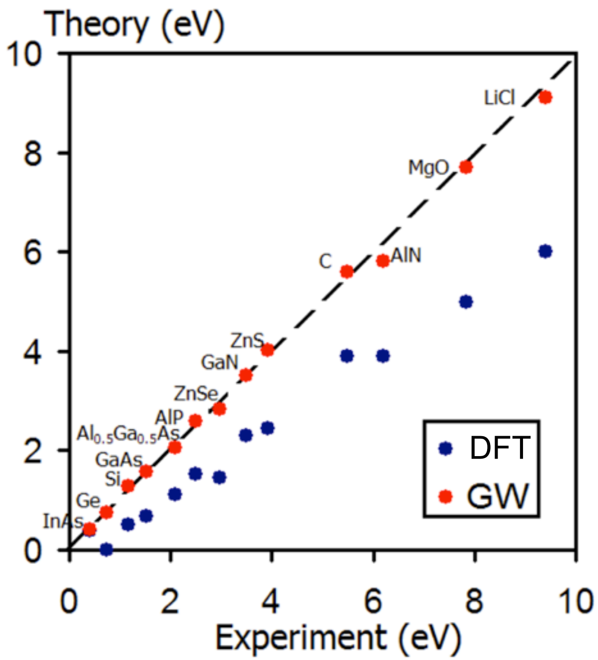


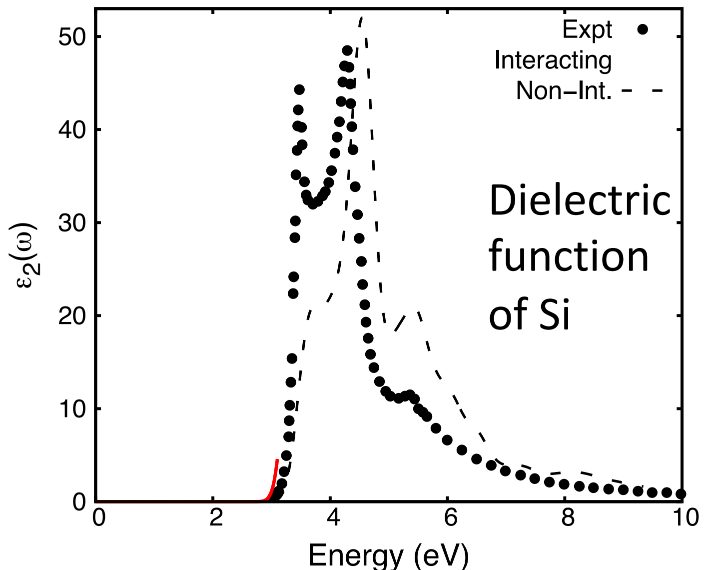
1. Droop: lower efficiency at high power
2. Green gap: lower efficiency for longer λ
3. Polarization fields separate electrons and holes
4. Composition fluctuations localize carriers

Can theory help?

Wu *et al.*, *Appl. Phys. Lett.* **101**, 083505 (2012)

Calculations of *functional* properties





Deslippe et al. , Comput. Phys. Commun. 183, 1269 (2012).

Density functional theory — GW method — Bethe-Salpeter equation

- Structure
- Thermodynamics
- Kinetics

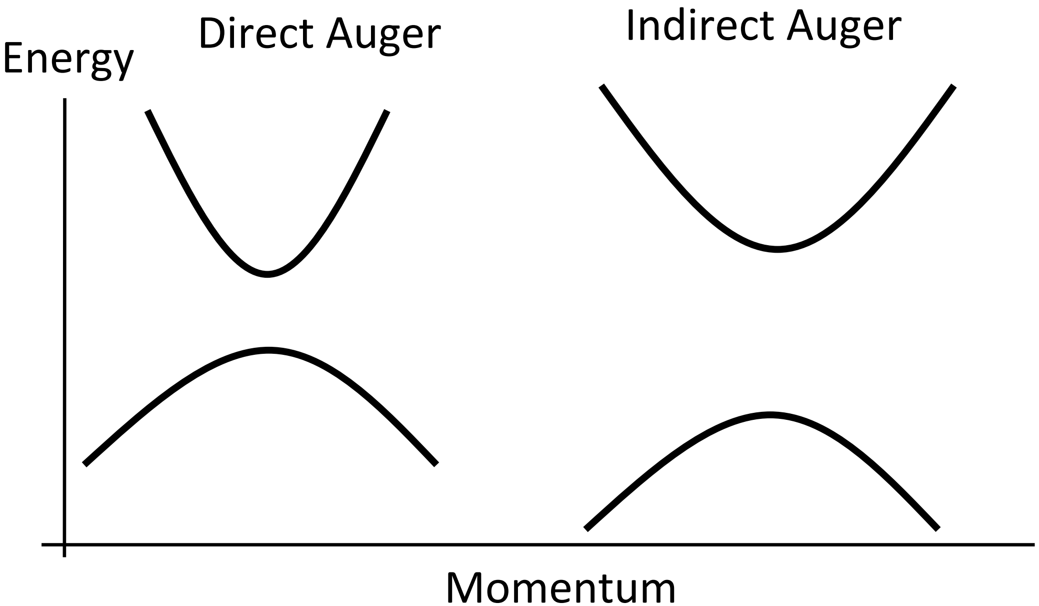
- Band gap
- Band structure

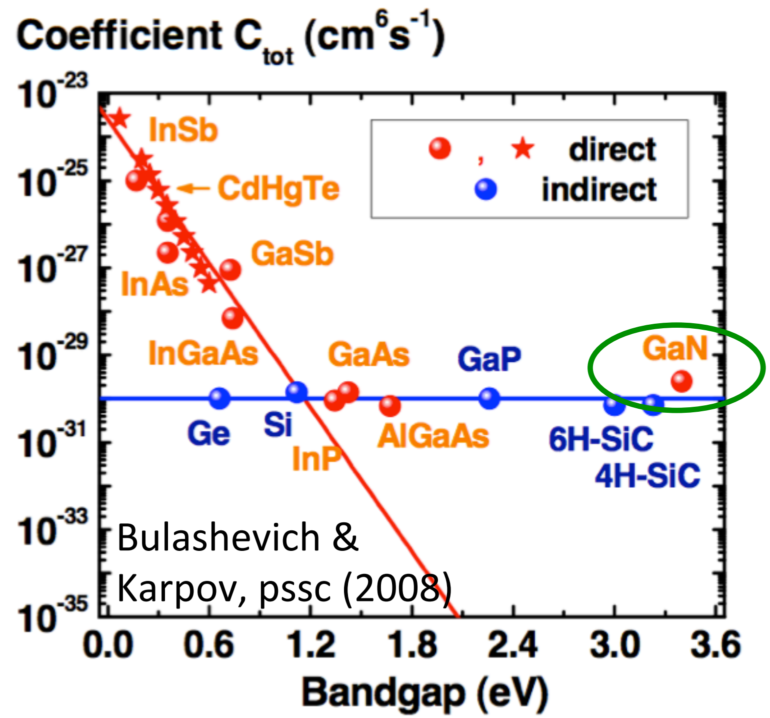
- Light absorption/emission
- Excitons

- Combine with device simulations to model LEDs
- Microscopic understanding of efficiency problems

Rondinelli and Kioupakis, *Annu. Rev. Mater. Res.* **45**, 491 (2015)

Auger recombination calculations



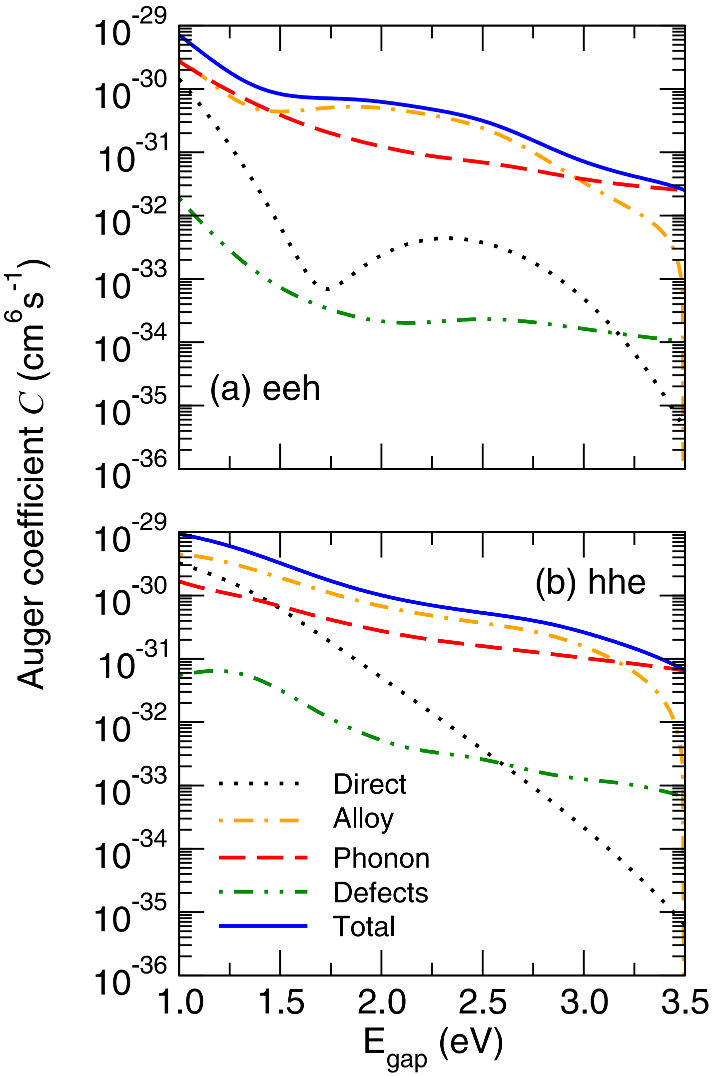


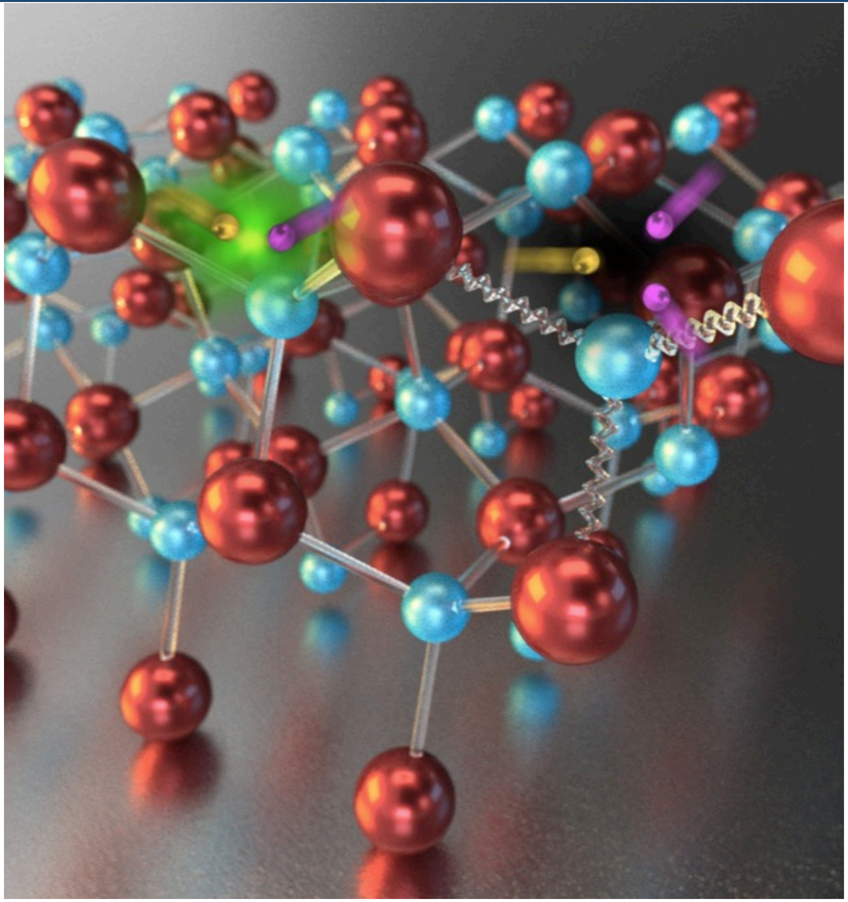
Calculations for direct Auger coefficient of GaN: $C \sim 10^{-34}$ cm^6s^{-1}

Too small: Experiment: $10^{-31} - 10^{-30}$ cm^6s^{-1}
Hader et al., *Appl. Phys. Lett.* **92**, 261103 (2008).

But what about higher-order indirect Auger?

Indirect Auger dominates in InGaN

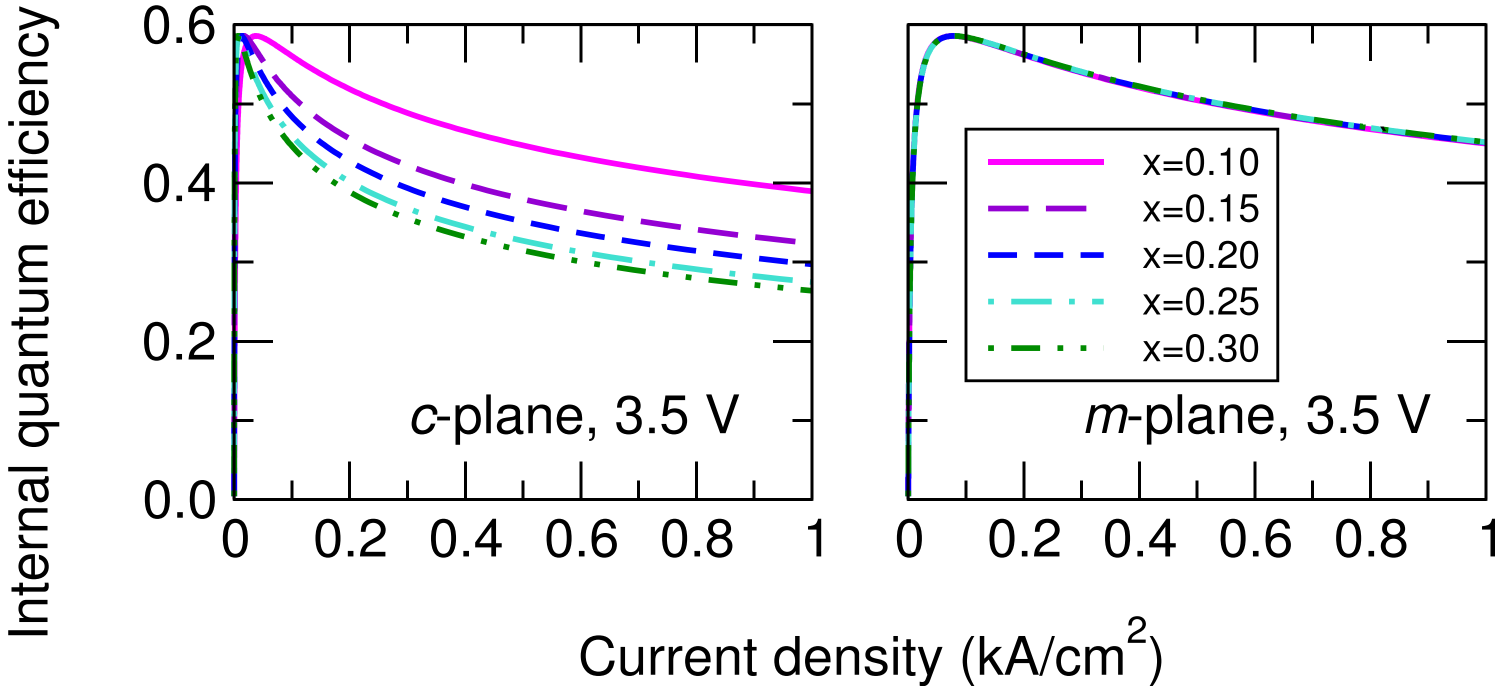




Exp: $C = 10^{-31} - 10^{-30}$ cm^6s^{-1}

Kioupakis, Rinke, Delaney, and Van de Walle, *Appl. Phys. Lett.*, **98** 161107 (2011)
Kioupakis, Steiauf, Rinke, Delaney, and Van De Walle, *Phys. Rev. B* **92**, 035207 (2015).

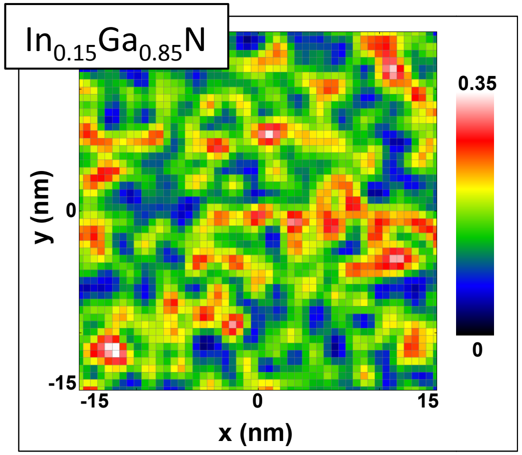
Polarization fields and droop



Green-gap problem: efficiency droop increases with increasing polarization fields, lower efficiency for LEDs at longer wavelengths

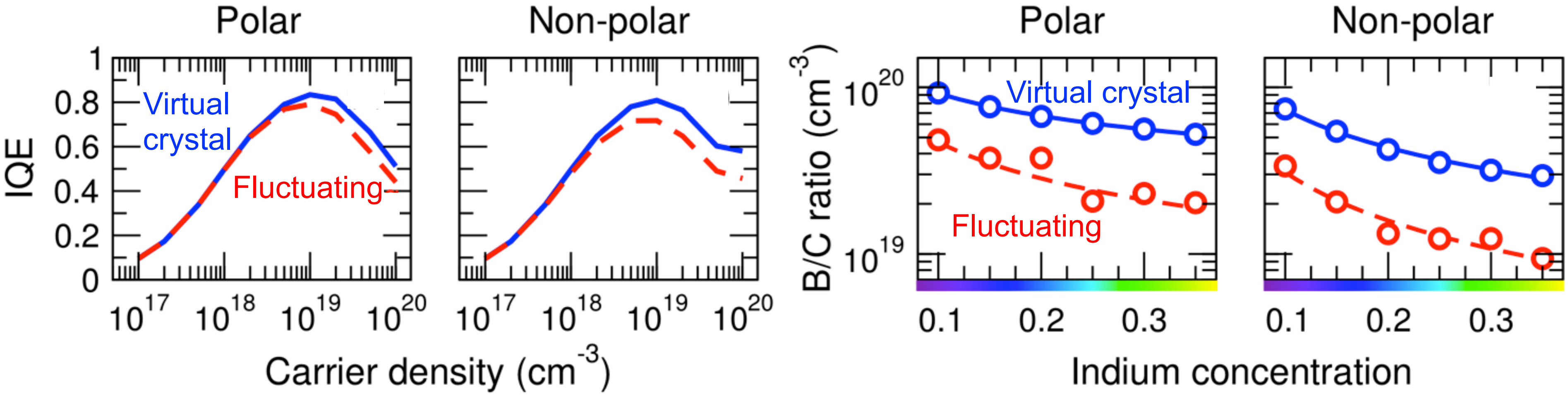
Kioupakis, Yan, and Van de Walle, *Appl. Phys. Lett*. **101**, 231107 (2012)

Fluctuations aggravate droop and green gap



Random composition fluctuations in InGaN localize electrons and holes.

- Separate electrons and holes → less overlap
- Break symmetry → enable recombination



Alloy composition fluctuations *decrease* the efficiency at high power and at longer wavelengths

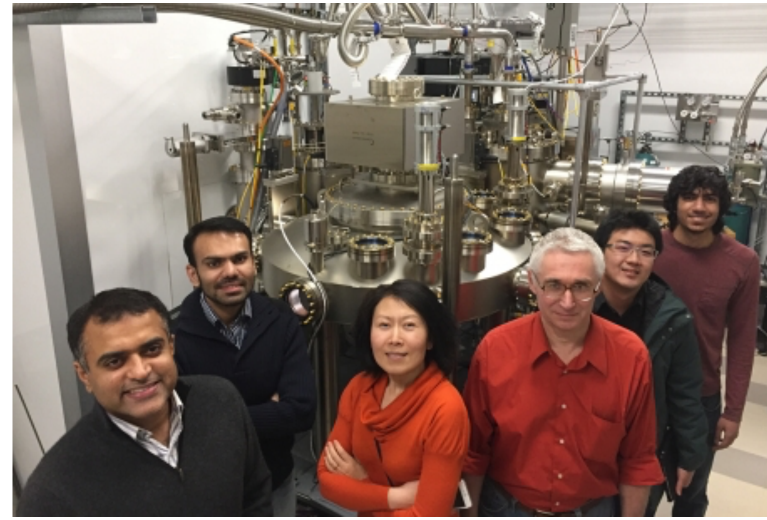
Christina Jones *et al.*, *Appl. Phys. Lett.* **111**, 113501 (2017)

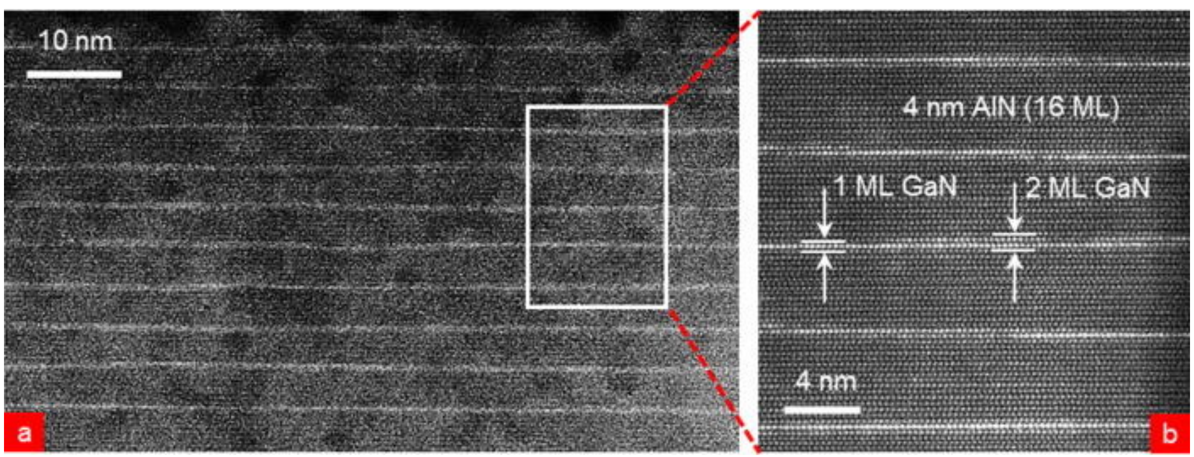
How to improve the efficiency?

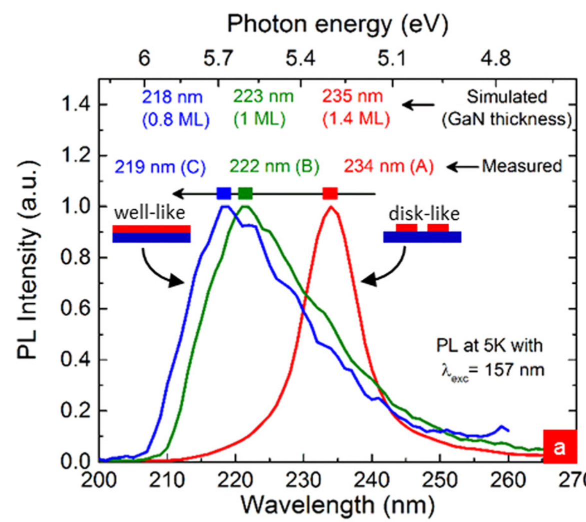
- Auger + polarization + localization = droop + green gap.
- Unfortunately intrinsic to InGaN
- Improvements:
  - Zincblende InGaN: no polarization fields
    - *But: requires new substrates*
  - Grow more quantum wells (reduce carrier density)
    - *But: poor carrier transport*
  - Grow a single thick quantum well (reduce carrier density)
    - *But: InGaN mismatched to GaN, dislocations if too thick*
  - Alternative: Make the quantum wells *thinner*

Atomically thin GaN for deep UV LEDs

- Grown by Jena and Xing at Cornell.
- Deep UV with atomically thin GaN in AlN.
- 40% IQE for deep UV emission at 219 nm

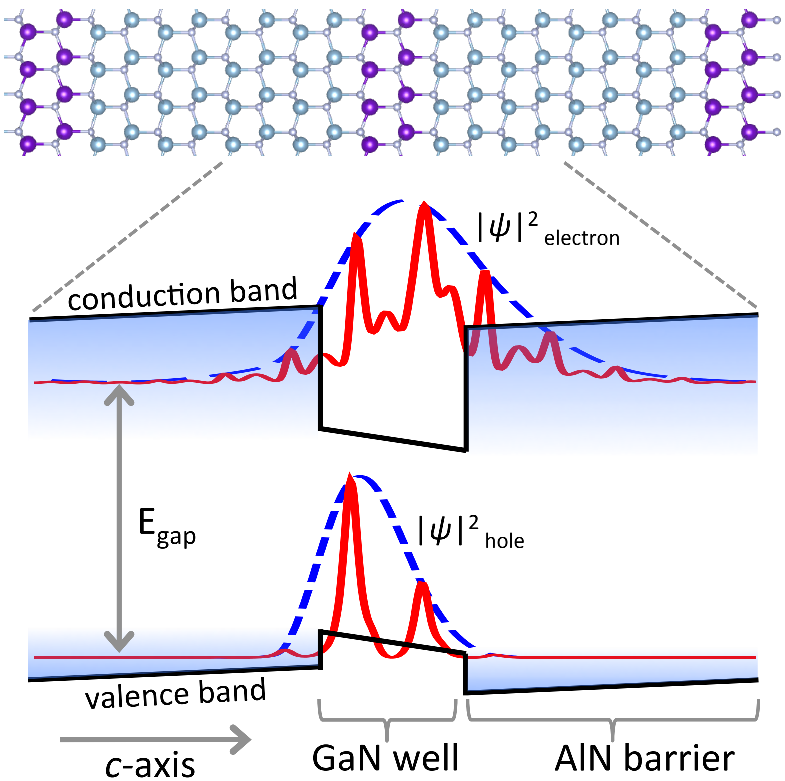


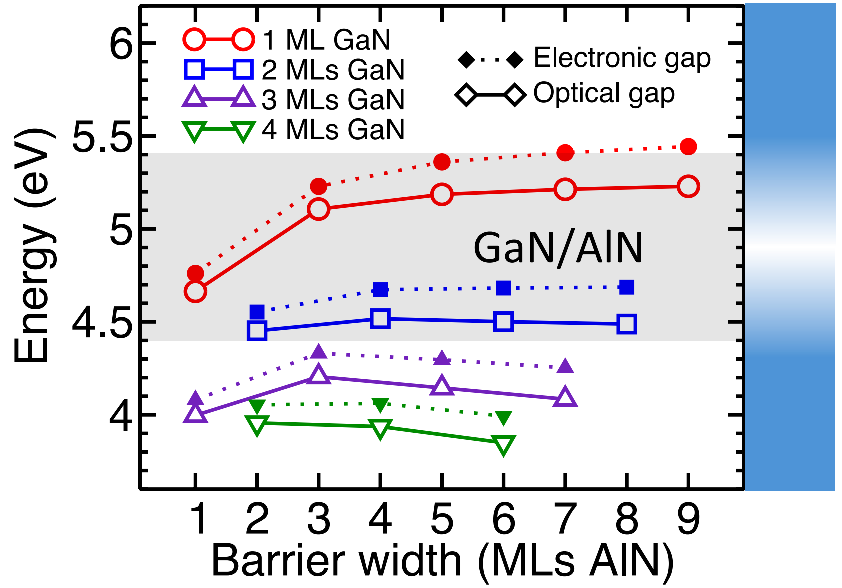


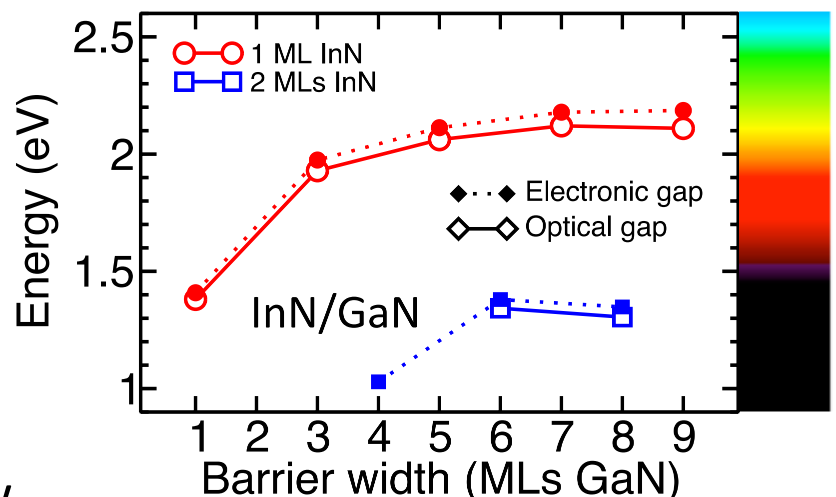


SM Islam *et al*., Deep-UV emission at 219 nm from ultrathin MBE GaN / AlN quantum heterostructures. *Appl. Phys. Lett*. **111**, 091104 (2017).

Atomically thin quantum wells







- Ordered compounds, reduced Auger
- Stark effect is weak
- Tune gap of InN in red/ amber/yellow

Bayerl, Islam, Jones, Protasenko, Jena, Kioupakis, *Appl. Phys. Lett.* **109**, 241102 (2016).

How to improve the efficiency?

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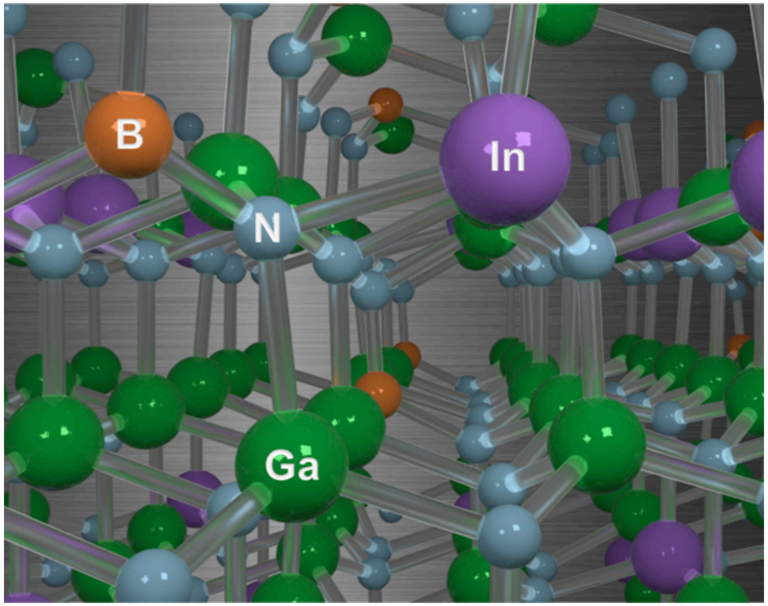
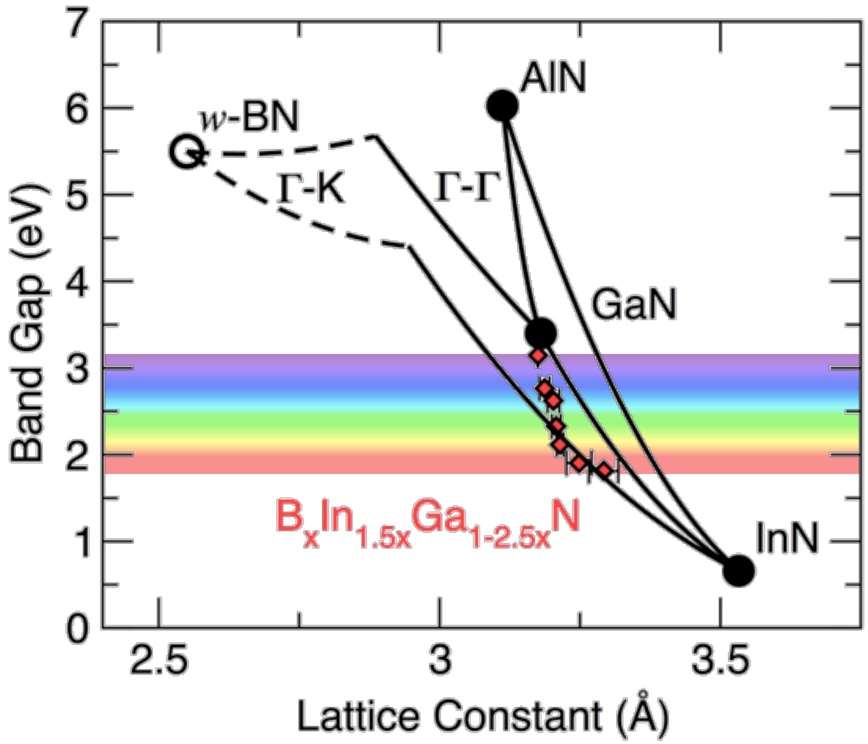
BInGaN: matched to GaN, visible gap





- BInGaN alloys with a 2:3 B:In ratio are approximately lattice matched to GaN.
- Their gaps (direct) span the entire visible range.
- Increase thickness → reduce Auger.

L. Williams and E. Kioupakis, BInGaN alloys nearly lattice-matched to GaN for high-power high-efficiency visible LEDs, *Applied Physics Letters* **111**, 211107 (2017).

Perspectives for future work

- Improved emitter materials:
  - Ultrathin quantum wells
  - Boron-containing InGa(Al)N
- Collaborations with predictive theory
  - Emitters materials
  - Phosphor design
  - Thermal transport
  - Defects
  - Growth kinetics